Earth Science Vision 2030

Modeling The Earth System

Critical Computational Technologies To Enable Us To Predict Our Planet's Future

Robert Ferraro
NASA Jet Propulsion Laboratory
Pasadena, CA, USA

Cecelia Deluca
National Center for Atmospheric Research
Boulder, CO, USA

Tetsuya Sato
Earth Simulator Center
Yokohama, Japan

Guy Brasseur
Max Planck Institut für Meteorologie
Hamburg, Germany

Eric Guilyardi
Centre for Global Atmospheric Modelling
University of Reading, United Kingdom

Requirements For Earth System Modeling

State of the Art Today

- Fairly accurate short term (3 day) weather forecasts over the continents
- Moderately accurate predictions of the major climate "states" such as the El Nino-Southern Oscillations (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the Madden-Julian Oscillation (MJO)

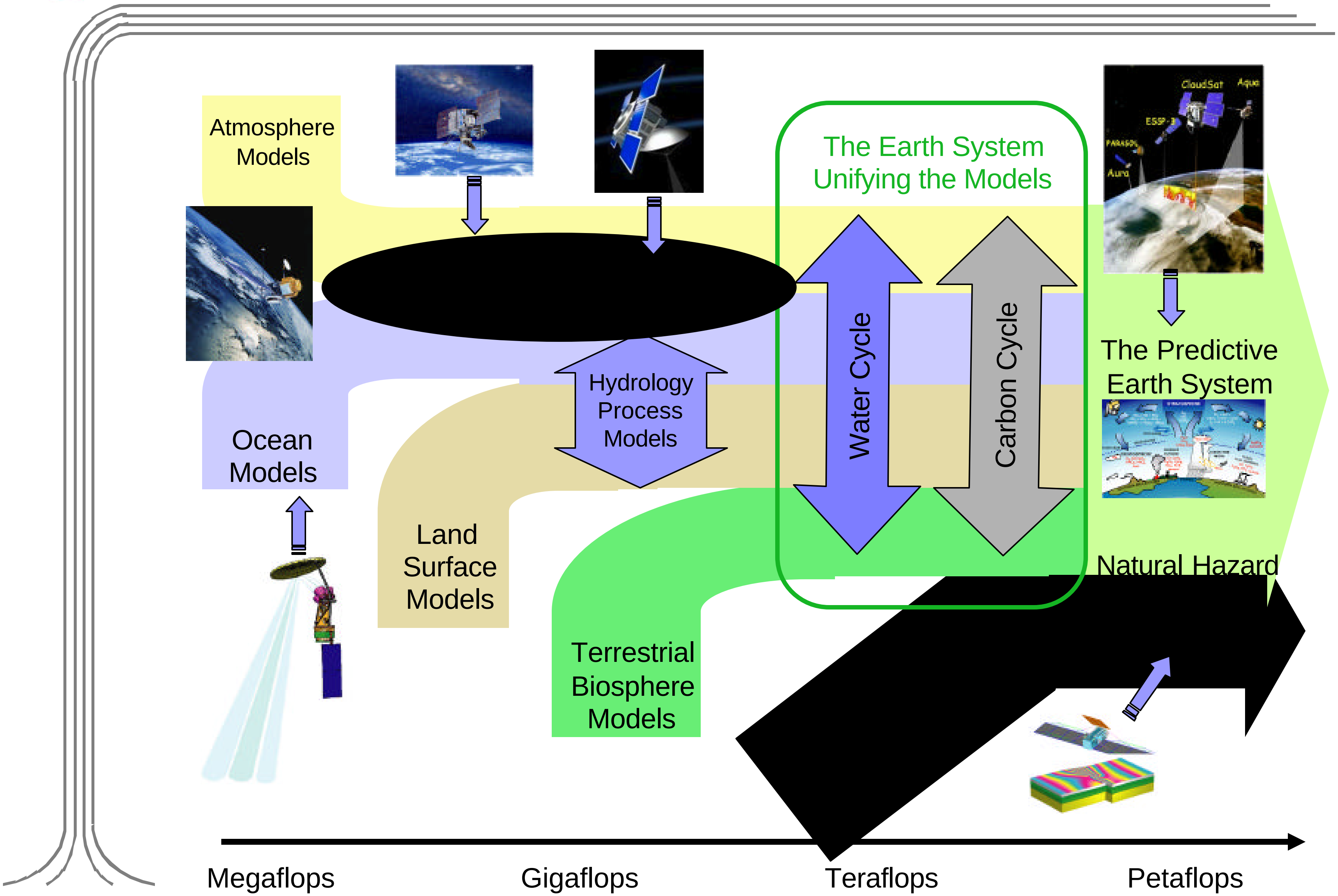
These are the result of:

- Thousand-fold increase in computational capability over the last 20 years applied to models
- Almost a Gigabyte/day of observational data ingested into models
- 3 decades of model development and process parameterization refinements

Requirements for Future Progress

- Development process for complex models needs to be easier
- Computing throughput must continue its exponential increase

Evolving Towards Predictive System Models



Computational Technology Requirements

NASA Earth Science Enterprise Computational Technology Requirements Workshop - May 2002

- **150 Modeling Researchers from the US convened to assess computational technology capabilities needed for modeling**
  - *Weather, Climate, and Solid Earth Panels*
- **Panels asked to define needed capabilities - not specific technology requirements**
- **Prediction capability goals for 2010 were used to frame the discussion**
  - *5-day weather forecast at > 90% confidence*
  - *3-day rainfall forecast*
  - *Hurricane landfall ±180 km 2 days in advance*
  - *Regional Air quality forecast 2 days in advance*
  - *6-12 month seasonal climate prediction routine*
  - *Improved temporal dimension of earthquake & volcanic eruption forecasts*
  - *…*
- **See paper for workshop report URL**

Workshop Results - 2010

Weather Prediction Requirements were the most computationally stressing

- **Climate, Solid Earth within a factor of 10**

Programming coupled models identified as major challenge

- **Frameworks, tools needed to increase productivity**

Algorithms for high end computing systems require continued development

- **Scaling to 1000s of processors**

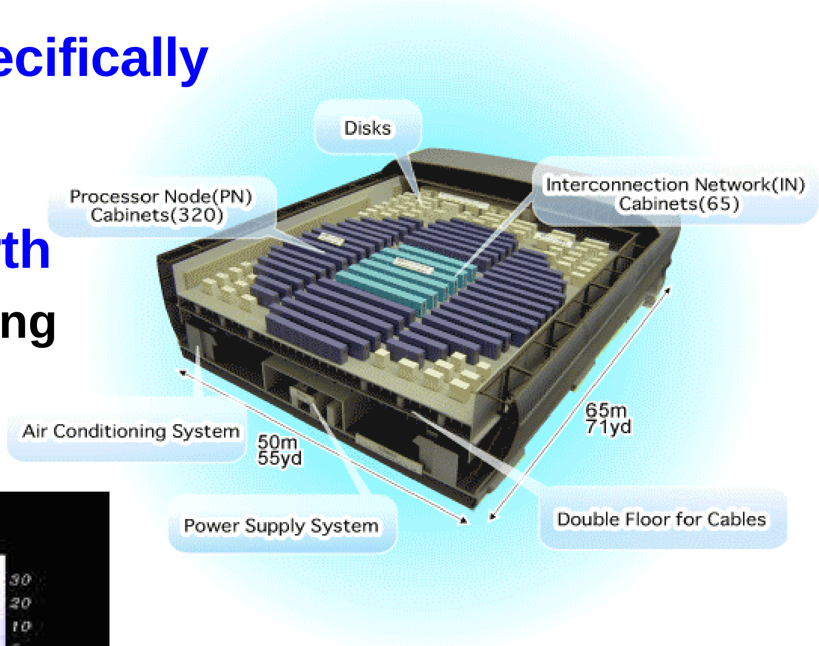
Computational Requirements Growth to Achieve a 5 Day Weather Forecast at 90% Confidence

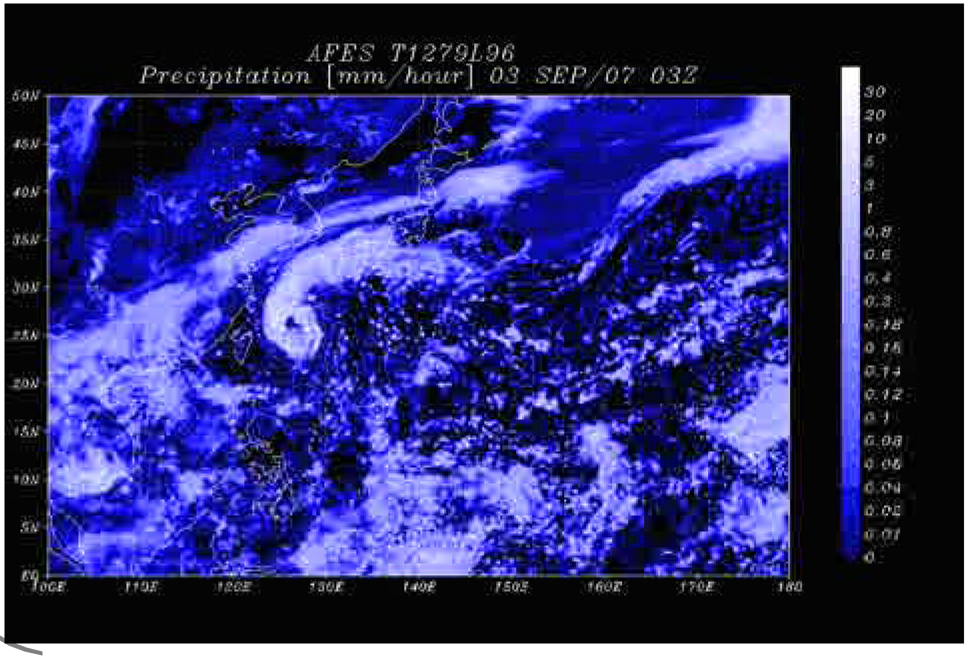
	2002 System	2010+ System
Resolution Horizontal Vertical levels Time step Observations Ingested Assimilated	 100 km 55 30 minutes 10^7 / day 10^5 / day	 10 km 100 6 minutes 10^{11} / day 10^8 / day
System Components:	Atmosphere Land-surface Data assimilation	Atmosphere, Land-surface Ocean, Sea-ice Data assimilation 100 Chemical constituents
Computing: Single Model Total System	 10 GFLOPS 100 GFLOPS	 50 TFLOPS 1 PFLOPS
Data Volume: Input (observations) Output (gridded)	 400 MB / day 2 TB / day	 1 TB / day 10 PB / day
Networking/Storage Data movement Internal External Archival	 4 TB / day 5 GB / day 1 TB / day	 20 PB / day 10 TB / day 10 PB / day

Japan Earth Simulator - The First Step

40 Teraflop NEC system built specifically to do quantitative prediction and assessment of variations of the atmosphere, ocean and solid earth

- **Most realistic mesoscale resolving climate model to date**





Twin typhoons evolving over the Philippine Sea simulated by the Super High Resolution Global Atmospheric Simulation (AFES)

Winner of the 2002 Gordon Bell award for performance

Modeling Achievements on the Japan ES

OGCM at .1 Degree

- threshold for a good representation of the western boundary currents and of the mesoscale eddy kinetic energy

Spectral Global Atmosphere (AFES) at 10 km

- Resolving mesoscale features in a global model
- Humidity/Precipitation predictions resolving cyclone features

Coupled atmosphere-ocean-sea ice model

- Simulations reproduce satellite imagery of regression of ice at both poles

Seismic wave propagation

- Simulation of wave propagation in the Tokyo earthquake from 50 years ago

Other examples

- Thermal conductivity of carbon-nano-tube and fullerene dynamics
- Biopolymers
- Propulsion dynamics

Managing Model Complexity

Programming burden for developing coupled multi-disciplinary models is high

- **Current Models are not scientifically or technically interoperable - impeding collaborations among model developers**
- **Incorporating new models or algorithms requires substantial code modification**
- **No interoperability standards exist for high end modeling**

Achieving the Earth system modeling vision will require new approaches to complex modeling applications development

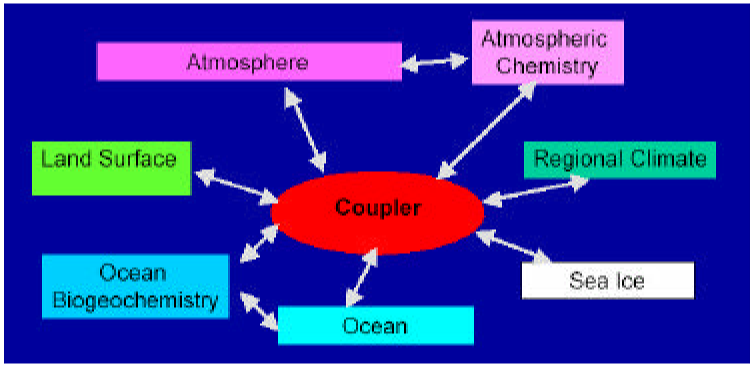
- **National and international collaborations to bring models together and benefit from the scientific diversity of the community**
- **Modeling environments that make it easy to collaborate**
- **Standard methods for assembling collections of models into an application to address specific science problems**
- **Standard underlying representations of basic modeling entities (e.g., grids, fields, partitions, transformations, data movement, etc.)**

PRISM & ESMF are the beginning of such environments

Program for Integrated Earth System Modeling

EC funded project to

- develop a framework for seamlessly coupling climate model components
- Promote standard interfaces for model components to a coupler that manages data exchange and synchronization



PRISM Framework Architecture

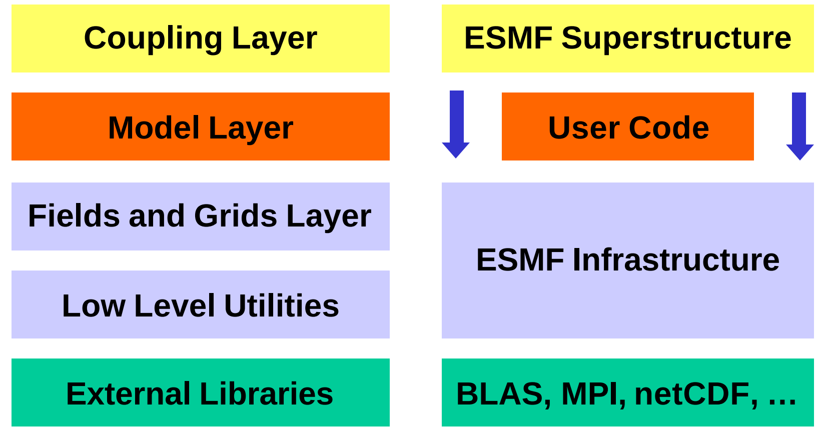
Prism Key Objectives

- Provide Software Infrastructure to
  - *Easily Assemble Earth System model components*
  - *Launch/monitor complex/ensembles Earth system models*
  - *Access, analyze and share results across a wide community*
- Share development and maintenance burdens
- Let scientists spend more time on science
- Define and promote community standards
  - *Increase scientific and technical modularity*
  - *Ensure high performance across a variety of platforms*

The Earth System Modeling Framework

NASA funded project to

- Develop a framework to enable a common standard architecture for Earth System Models
- Simplify future development and evolution
- Enable interoperability of model components in climate, weather and data assimilation applications



Code hierarchy (left) in the ESMF framework (right)

Key ESMF Development Objectives

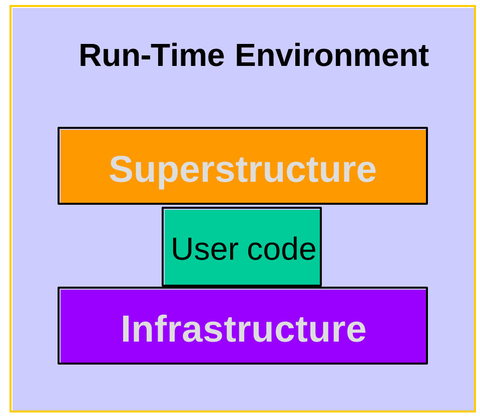
- Component based modeling architecture
- Robust, flexible tools to enhance ease of use, performance portability, interoperability, and code reuse
- Standardized representations of fields and grids
- Common low level utilities tool box

Complementary Approaches

Architecture for Model Interactions, Control

ESMF

Standardized Representations of Grids, Fields, Partitions, Utility Functions



Unified Runtime Architecture for Setup, Execution, Post-processing

PRISM

Coupler Managing Synchronization & Control with Standardized Interface to Models

Initial Focus

- ESMF is focusing on the infrastructure (Grids, Fields, Partitions, Utilities)
- PRISM is focusing on the coupling superstructure and the associated runtime and analysis environment

Coordination is Increasing

- Regular interactions between efforts has started
- Collaboration to ensure compatibility of key standards and interfaces
- Expectation is that each project will leverage the other's work

Summary

- **Achieving a unified earth system modeling capability will require sustained growth in computing capability**
- **Enabling the science will require continued development of modeling frameworks to ease the programming burden**

Progression of Modeling Capability and Complexity and the Computing Performance Required to Sustain It

	Today	2010	2030
Models	Single Discipline Models Coupled Ocean-Atmosphere Models for Climate Prediction Single Discipline Data assimilation	Coupled Ocean – Atmosphere – Land Surface Models with multi-model data assimilation 4X resolution improvement Multi-component solid earth models with data assimilation	Integrated multidisciplinary Earth System Models with 10X additional resolution improvement, fully consistent all component data assimilation, validated prediction capability for 2 week weather, interannual climate, moderate confidence fault hazard predictions
Performance	1 – 10 TeraFLOPS Sustained (Japan Earth Simulator)	100s of TeraFLOPS – PetaFLOPs Sustained	100s of PetaFLOP
Dedicated Networks	1 Gb/s sustained	100Gb/s sustained	10 Tb/s sustained
Memory (RAM)	10 TB	50 TB	10 PB